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Nitrogen application decision-making under climate risk in the U.S. Corn Belt

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ABSTRACT

Nitrogen fertilizer is one of the most important inputs to corn production and farmers manage their crop by deciding how much to apply, when to apply it and how to apply it to maximize their yields and resulting profit. There is risk inherent in crop fertility management because once nitrogen is applied to the soil it is no longer immobile and cropland is subject to loss of this costly input under different weather conditions. Days suitable for field work, a farm's machinery set, and weather conditions determine when field preparation and planting activities are completed each year. This paper documents the methods and data used to evaluate the economic costs and benefits of the agronomic practice of "splitting" nitrogen fertilizer—applying some at or just before planting and a second application after the plant has already emerged and is in greatest need of nutrients. An example of how to use the free online decision support tool Corn Split N_{DST} (splitn.agclimate4u.org) to evaluate the climate risk and economics of post-planting N applications is developed to illustrate the application of methods described.

1. Introduction

Risk from adverse or extreme weather events is a persistent condition for agriculture that has a strong impact on crop yields. The risk of yield losses from different types of weather events differs by climate and cropping system. Yield and revenue risk are the focus of crop insurance and forward pricing strategies regularly employed to manage the financial risk of farming. The weather experienced in a given year combined with farm management and soil characteristics are what determine the harvested yield on a given farm, and optimizing planting and fertilization is essential to achieve the best economic results possible. The focus of this paper is on decision-making about nitrogen (N) fertilizer application timing for corn production in the Corn Belt region of the Midwestern U.S. Fertilizer is one of the most expensive inputs to corn and it is also one of the most important to ensure that corn crop growth is not N limited and achieves the highest yield possible.

There are two main sources of climate risk that are most relevant for fertility management: nitrogen loss from soil and days suitable for fieldwork (DSFW). Weather—as the occurrence of climate at a given point in time—interacts with soil and farm management to determine the number of days that are suitable to perform field work (e.g., the number of days that soils are not too wet to prevent tillage, fertilizer application or planting activities) which constrains the number of days available to complete spring field preparation and planting in a timely fashion. Delayed planting because soils are too saturated

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and/or cold will affect yields at harvest (Myers and Wiebold, 2013). Weather between the time that N fertilizer is applied and when it is needed by plants for growth or grain production also determines the risk of N loss via leaching, runoff and denitrification (Scharf, 2015).

The prior literature on DSFW has focused mainly on a basic understanding of the usefulness of these data for farm management and planning (Griffin, 2009), or the applied use of historical DSFW data to support farm machinery sizing (Rotz et al., 1983; Rotz and Harrigan, 2005) and more general farm management optimization (Doster et al., 1983; Dillon et al., 1989; Etyang et al., 1998) in different production systems and locations. The practical importance of DSFW is evidenced by extension publications (e.g. Parsons and Doster (1980), Massey et al. (2007), Edwards (2015)), and regional (Griffin, 2016) and national (USDA-NASS, 2016) online data resources devoted to farm management decision support.

Farmers traditionally apply N to the soil in a single pass across the field, either post-harvest in the fall or in the spring before planting. Nitrogen, applied in various forms, may not be immediately available for uptake by plants, but once it is in nitrate form it can be taken up by growing plants or it may be lost to the environment. Early nitrogen application—before plants need it to grow—can result in significant losses due to weather factors (e.g. warm, moist soils between the time N is applied and plant uptake occurs). For this reason, agronomic recommendations from university Extension services generally encourage nitrogen fertilizer shortly before maximum crop uptake (Scharf, 2015; Vitosh et al., 1995). Research has shown that splitting the application of N with one application before or around the time of planting and a second application after planting when there is greater demand for N from the crop can reduce total nitrogen use resulting in economic savings for the farmer and/or reduce nitrogen loss to the environment resulting in reduced negative externalities to society (Curran and Lingenfelter, 2015; Bundy, 2006).

A second application of nitrogen to growing crops can be done using high clearance ground equipment or aerial applications. Using ground equipment allows for greater management flexibility but a shorter application window than aerial applications. Aerial applications are limited to dry nitrogen sources, to reduce foliar burn (Mengel, 1996), and the use of a nitrogen stabilizer is recommended (Emmert, 2016), making the product more expensive. Availability and price may also be higher for aerial application depending on location.

There are some risks involved with a split N application strategy. The economic risk of greater costs being incurred if two passes through the field with machinery are required. The climate risk of the second application (if conducted using ground application equipment) being hindered by soils that are too wet resulting in insufficient N when a second application is needed that may result in lower yields. The objective of this work is to develop a decision support tool (DST) that helps farmers evaluate the economics and risk of split N application, using ground application equipment, based on historical data on DSFW and temperature that determines crop development rates. To this end, we developed the Corn Split N DST that combines experimental data on crop fertility management with a farmer's yield goal, N application rate and timing, and N and corn prices to estimate the economic costs and benefits of post-planting N application. This work was done as part of the Useful-to-Usable project (www.agclimate4u.org) to develop decision tools for farmers and their advisors to help them manage for climate risks to maize based cropping systems. A survey conducted at the outset of the project identified a strong demand among farmers and their advisors for a decision support tool for N management.

The Split N tool developed and documented in this paper has its origins in the Probable Fieldwork Days spreadsheet model developed by Gerlt et al. (2016) at the University of Missouri (http://fapri.missouri.edu/farmers_corner/tools/index.asp) to manage the risk of not completing cropping operations in an acceptable amount of time due to fieldwork and time constraints with a given machinery complement. The Split N tool builds upon the use of historical DSFW data to evaluate the probability of completing fieldwork for a specified number of acres over a specified range of dates by incorporating growing degree day based crop development, economic costs and benefits, agronomic information on yield penalties, and user customization of yield goal and initial N application amounts.

2. Data and methods

Two main categories of data sources underlie the Split N tool—user-provided inputs and data contained within the tool for historical fieldwork days, growing degree days (GDDs) and yield penalties for not completing the post-planting N application. After selecting the farm location, the most critical user inputs are the planting date, farmer's yield goal they manage for in bushels per acre, and the amount of N initially applied at or before planting in pounds per acre. These and related inputs are shown in Fig. 1. The default values that appear in the tool after a user selects their location from a map come from different sources; a summary of the main variables and sources is contained in Table 1 and the text that follows.

The default value for the yield goal is the county average yield in the user-selected county for the most recent year data are available from the USDA National Agricultural Statistics Service (NASS). The GDD calculations are based on gridded daily temperature data contained in the Applied Climate Information System maintained by the NOAA Regional Climate Centers based on the user-selected location. Growing degree days are calculated following the 86/50 method for ceiling and floor temperatures (Farenheit) to determine the corn growth stage as a proxy for plant height in the field. The 86/50 method is based on the principle that biological growth is primarily controlled by temperature, with temperatures above 50°F contributing to crop growth up to the ceiling temperature 86°F, above which the growth rate declines. The height of the corn in the field is important because our model is for ground application of in-season nitrogen. Other metrics, in addition to or instead of GDDs, could be used to model crop development but this is not the focus of the current research.

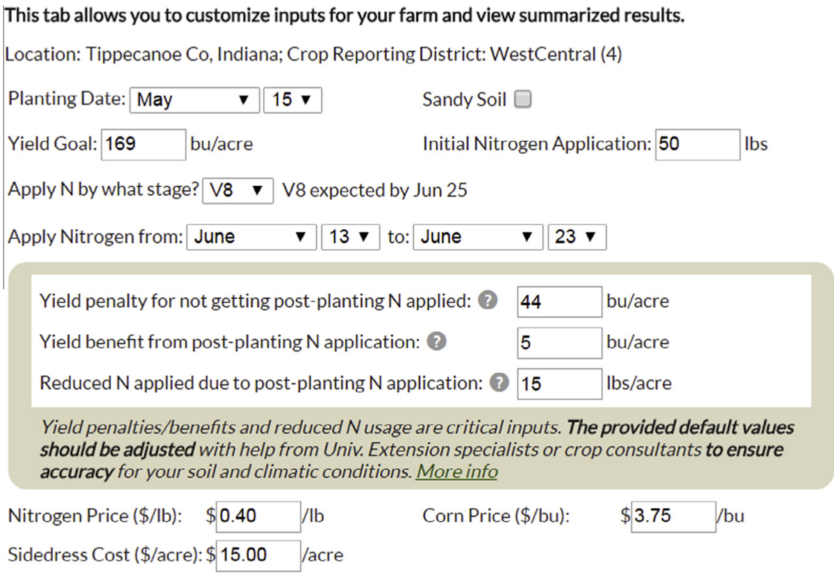


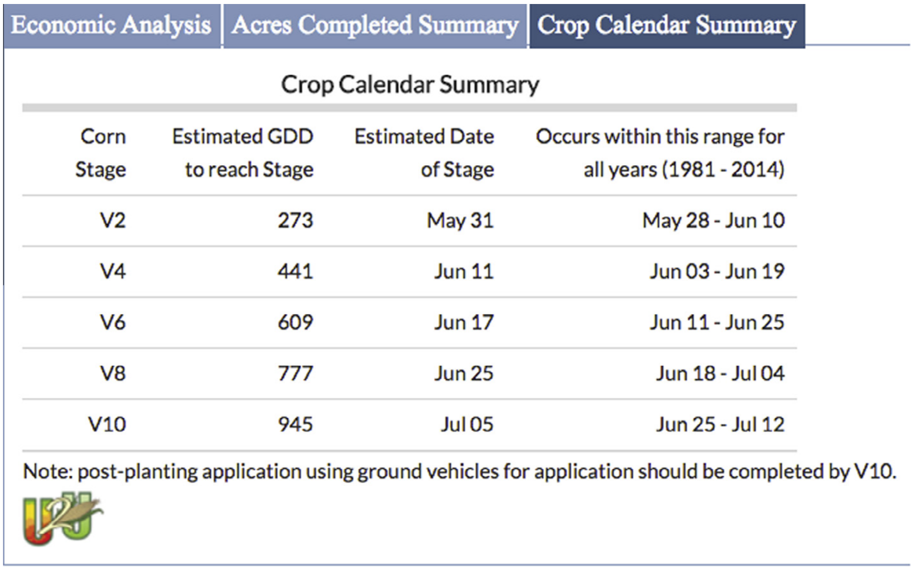
Fig. 1. Screenshot of planting and fertilization inputs and defaults.

Table 1
Summary of key variables and calculated parameters used in the Corn Split N_{DST}.

Variable	Description	Source(s)
Days suitable for fieldwork (DSFW) • Observed historical data: IL, IN, IA, KS, MO • Empirical predictive model: MI, MN, NE, ND,OH, SD, WI	Number of days (0–7) that field conditions were suitable to perform fieldwork	Weekly Crop Progress and Condition Report, USDA National Agricultural Statistics Service (NASS)
Yield (default value overridden by user input)	Corn yield (bushels/acre) for most recent year available	County corn yield, USDA NASS
Corn growth stage(approximated)	Corn growth stage calculated based on current year and/or historical mean growing degree-days (GDDs) accumulated after planting date	Corn development:Abendroth et al. (2011) Temperature: Applied Climate Information System (ACIS) (2016)
Yield penalty	Reduction in potential yield if cannot complete post-planting N application based on percentage of maximum achievable at a given N rate	Corn Nitrogen Rate Calculator (2015), Camberato and Nielsen (2016); and additional university extension specialists (see U2U (2016) for details)

After a user inputs the planting date, the tool calculates the approximate dates when the vegetative growth stages V2–V10 will occur based on the accumulation of GDDs at the selected location (see Crop Calendar Summary output in Fig. 2). The relationship between accumulated GDDs and plant growth are based on Abendroth et al. (2011). Corn emergence is assumed to occur at 105 GDDs post planting, although the scientific literature states emergence can occur at 90–200 accumulated GDDs post planting depending on factors such as ground cover and tillage practices. The actual GDDs accumulated since planting up to the current day are used to estimate the growth stage, and corn growth beyond the current day is estimated based on the 30-year (1981–2010) average GDD accumulation at the chosen location. The user can select the growth stage by which they want to apply the post-planting application, the tool tells the user the date when the selected stage is expected to occur. This information can then be used to select the starting and ending dates for applying N. Post-planting applications are recommended by stage V8 and most surface application equipment is unable to apply N beyond the V10 stage because plants are too tall.

The default yield penalty for not being able to complete the post-planting N application is calculated as the percentage of maximum yield attainable at the initial N application rate multiplied by the user specified yield goal. The default penalty is individualized by state and within states based on the user-selected location inside states with many trials in different regions (Split N DST online documentation (U2U, 2016) has additional details). The state default yield penalties are derived from the percent maximum yield data contained in the Corn Nitrogen Rate Calculator (2016) website, or from field trial data that underlie individual state N application guidelines or recommendations (e.g. Camberato and Nielsen (2016) in Indiana) for those states not included in the corn N rate calculator. In the case of Kansas and Missouri, the values are assumed to be equal to those from N rate trials conducted in southern Illinois because no state data were available. Data were obtained


Economic Analysis | Acres Completed Summary | Crop Calendar Summary

Crop Calendar Summary

Corn Stage	Estimated GDD to reach Stage	Estimated Date of Stage	Occurs within this range for all years (1981 - 2014)
V2	273	May 31	May 28 - Jun 10
V4	441	Jun 11	Jun 03 - Jun 19
V6	609	Jun 17	Jun 11 - Jun 25
V8	777	Jun 25	Jun 18 - Jul 04
V10	945	Jul 05	Jun 25 - Jul 12

Note: post-planting application using ground vehicles for application should be completed by V10.

Fig. 2. Screenshot of crop calendar summary showing approximate growth stage dates.

through personal communications with state extension fertility specialists for North Dakota and South Dakota, and are based on irrigated corn only for Nebraska (Dobermann et al., 2011).

The N application dates are used, together with the corn acreage, equipment and working hours information shown in Fig. 3. Calculated hours needed to complete the post-planting N application are a function of the specified machinery parameters (implement width, speed and field efficiency) and acreage to be fertilized. The average days suitable for fieldwork is based on the DSFW for the selected period (in Fig. 1). The average hours suitable is the average days suitable times the number of hours in the field per day. The model defaults to daylight hours in a day during the selected period. If farmers are not constrained by daylight or have other responsibilities that limit their time, the user can select the custom hours option and enter their expected work day length.

If the calculated hours needed are greater than the average hours suitable, then the probability of being able to complete N application is likely to be unacceptably small. Different farmers desire different probabilities of completing field work with their equipment complement. The percentage of years that the post-planting N application would be completed for different acreages given the equipment and work hours input in Fig. 3 are reported as output from the tool as in Fig. 4. The highlighted row contains the final application date and percentile for the number of acres the user entered into the tool.

Historical field work days are one of the most important pieces of data contained within the tool because they constrain the total available work hours to only those hours when N can actually be applied. The DSFW are reported weekly during the

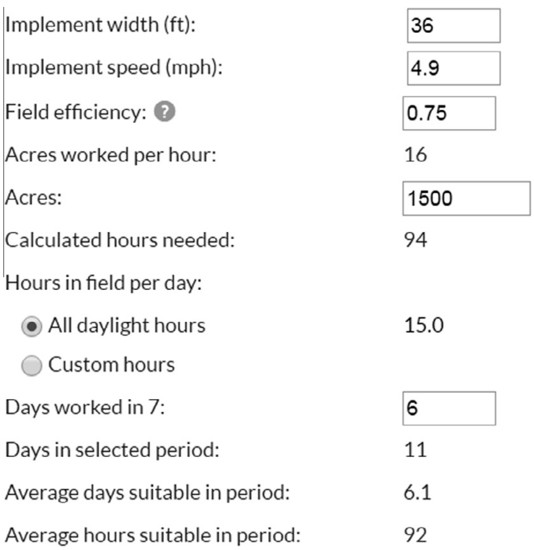


Fig. 3. Screenshot of equipment and work hour inputs and outputs.

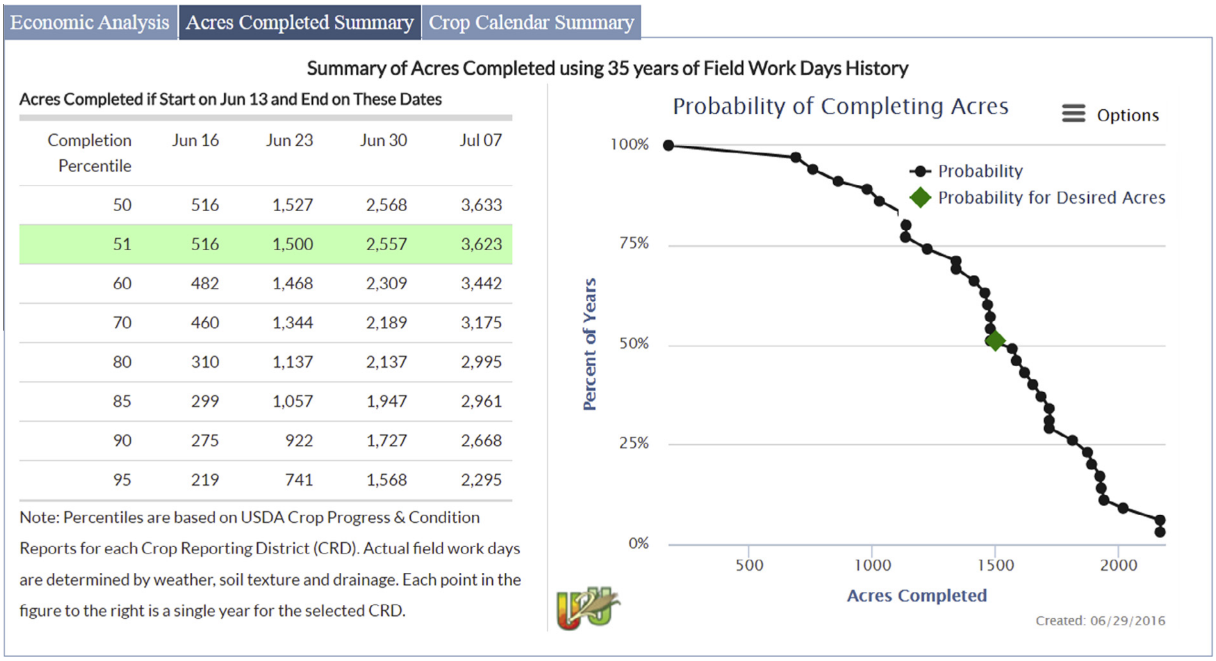


Fig. 4. Screenshot of acres completed summary showing percentage of years various acreages completed by reported dates.

growing season for each state by the USDA's NASS in the Crop Progress and Condition report. The majority of all states report a single number between zero and seven for the entire state. Because weather and soil conditions that ultimately determine DSFW are considerably different across such a large geographic area, state-level data are not expected to provide very accurate estimates for local areas. Illinois, Indiana[1], Iowa, Kansas and Missouri report DSFW at the USDA crop reporting district (CRD) level; a CRD is a group of contiguous counties in a single state. Data from these states were used to estimate the statistical relationship between historic weather data and the area-weighted soil drainage class[2] to predict DSFW at the CRD level that could be applied to those states without CRD reports—Michigan, Minnesota, Nebraska, North Dakota, Ohio, South Dakota and Wisconsin. Therefore, the weekly DSFW values in the Split N tool for these seven states within the Split N tool are estimated weekly values, not historical observations.

The empirical equation below for DSFW was estimated using a random effects model:

$$
\begin{aligned}
\widehat{\mathrm{DSFW}}_{CRD} = {} & -5.56285 + 0.210292 * (\text{average max temp}) - 0.00237 * (\text{average max temp})^2 \\
& - 0.23367 * (\text{average min temp}) - 0.00251 * (\text{average min temp})^2 \\
& + 0.005212 * ((\text{average max temp}) * (\text{average min temp})) \\
& - 1.12549 * (\text{total precipitation}) + 0.113922 * (\text{total precip})^2 \\
& + 0.055012 * (\text{average max temp the previous week}) \\
& - 0.03594 * (\text{average min temp the previous week}) \\
& - 1.01346 * (\text{total precip the previous week}) \\
& + 0.00868 * ((\text{precip in previous week}) * (\text{average min temp current week})) \\
& + 0.021476 * (\text{annual time trend}) - 0.00025 * (\text{annual time trend})^2 \\
& - 0.45365 * (\text{spring indicator}) + 0.374839 * (\text{fall indicator}) \\
& - 0.42513 * (\text{winter indicator}) + 3.065181 * (\text{soil drainage class index}) \\
& - 0.43322 * (\text{soil drainage class index})^2
\end{aligned}
$$

[1] Prior to 1995, Indiana DSFW data were reported on a 10-day interval. These data have been converted to a 7-day interval based on the average fieldwork days per day in the reporting interval. For example, if 10 days were suitable for field work in a 10-day reporting period this is 1 work day per calendar day. This conversion process is imperfect, but results in a daily moving average over the entire growing season and allows for the data to be assimilated into a weekly time-step consistent with all other state data.

[2] Soil drainage class is included in the model to control for spatial variation in soil types that interact with precipitation and temperature to determine DSFW. This is an area-weighted calculation for each CRD based on the percentage of land in each drainage class within the CRD ranging from excessively drained (sands) to very poorly drained soils.

This equation was estimated to control for soil drainage class, annual trend in weekly DSFW, seasonal effects, maximum and minimum temperature, precipitation, the lagged effects of the prior week precipitation, and interactions between prior week precipitation and current week temperature that may influence soil saturation in a given week. The parameters reported were estimated based on the observed DSFW, weather and soil drainage class from the five states that issue weekly CRD-level fieldwork reports. This estimated model predicts observed DSFW within plus or minus one day (RMSE = 0.9989) per week. Standard econometric procedures were followed to perform out of sample prediction tests using randomly selected subsets of the weekly observed data to predict DSFW in the remaining CRDs with weekly reports not used in the estimation sample. The details of the econometric estimation procedure and out of sample prediction performance can be found in Gramig and Yun (2016). Model prediction performance was robust to different randomly selected estimation samples. All weather data used to estimate the model were provided by the Midwestern Regional Climate Center based at the University of Illinois (http://mrcc.isws.illinois.edu/), all soils data were processed from the USDA-NRCS SSURGO database (http://sdm-dataaccess.nrcs.usda.gov/), and seasonal indicators were constructed based on solstices and equinoxes assumed to occur on the 21st of March, June, September and December of each year.

The remaining outputs reported to the user by the Split N tool are the economic calculations presented in Fig. 5. The Economic Analysis tab summarizes specific information contained in the Acres Completed and Crop Calendar summary tabs depicted in Figs. 3 and 4. Namely, the number and percentage of years that the post-planting N application would have been completed over the number of years that data are available (e.g., 35 in the example depicted in the figures above), and the maximum (Best/Max Case) and minimum (Worst Case) number of acres completed over the same set of years. Two pieces of economic information are likely of greatest interest: the expected net benefits (or loss) for the input number of acres and the net benefit from the average number of acres completed (if this number is less than input number of acres). The monetized net benefits are broken down into the additional cost of a post-planting surface application, any yield loss (due to the yield

Economic Analysis | Acres Completed Summary | Crop Calendar Summary

Economic Analysis using 35 years of Field Work Days History

Scenarios	Acres	Units/acre	Dollars/unit	Total Dollars
Input Acres Completed (completed 1500 acres post-planting N application 18 years of 35 years, or 51% of years)				
Additional cost of post-planting fertilizer application	1500	1	$15.00	$(23,000)
Yield loss due to unfertilized acres	0	44	$4.50	$0
Yield gain due to post-planting fertilization	1500	5	$4.50	$34,000
Nitrogen saved (lb) due to post-planting fertilization	1500	15	$0.40	$9,000
Net Benefit of Post-planting N application on 1500 acres				**$20,000**
Average Acres Completed (completed an average of 1475 acres post-planting N application 21 years of 35 years, or 60% of years)				
Additional cost of post-planting fertilizer application	1475	1	$15.00	$(22,000)
Yield loss due to unfertilized acres	25	44	$4.50	$(5,000)
Yield gain due to post-planting fertilization	1475	5	$4.50	$33,000
Nitrogen saved (lb) due to post-planting fertilization	1500	15	$0.40	$9,000
Average Net Benefit of Post-planting N application on 1500 acres				**$15,000**
Worst Case (At least 172 acres of post-planting N application completed in all years)				
Additional cost of post-planting fertilizer application	172	1	$15.00	$(3,000)
Yield loss due to unfertilized acres	1328	44	$4.50	$(263,000)
Yield gain due to post-planting fertilization	172	5	$4.50	$4,000
Nitrogen saved (lb) due to post-planting fertilization	1500	15	$0.40	$9,000
Worst Case Net Benefit of Post-planting N application on 1500 acres				**$(253,000)**
Best/Max Case (could have completed up to 2171 acres 2 year(s) of 35 years, or 6% of years)				
Up to 2171 acres of post-planting N application completed	2171			
Breakeven Number of Acres (Post-planting N revenue equal costs in 23 years of 35 years, or 66% of years)				
Number of acres (out of 1500 acres) requiring post-planting N application to breakeven	1401			

Note: This information is educational and should not be the sole source of information used to make a management decision.

Total Dollars are rounded to nearest thousand.

Fig. 5. Screenshot of economic analysis showing the expected net benefits of a post-planting N application.

penalty) from acres that were not able to be fertilized, the yield gain from delaying application after planting, and any N savings from applying less N than would have been done pre-planting. The worst-case economic outcome is included because many farmers are risk averse and want to know this information when evaluating management changes.

3. Interpreting results for decision-making

Figs. 1–5 depict an example scenario for a 3000 acre farm using a corn-soybean rotation located just outside of West Lafayette, IN that planted corn on May 15. This farm is expected to have 1500 acres of corn in any one year receiving a split N application. This farm manages its corn crop to achieve 169 bushels per acre yield and evaluates the economics and risk of applying 50 lb of N per acre prior to planting and applying the remaining N by the V8 growth stage that is estimated to occur by June 25 based on the current year GDD accumulation to date and the historic mean accumulation of GDDs going forward in the growing season. The yield penalty default was not changed for this example and indicates a 44 bu/ac reduction in the yield goal—from 169 to 125 bu/ac—on any acres if the farmer is unable to apply the post-plant N. The economic calculations are driven by the prices entered by the user. In this case, the prices used are the defaults for the 2016 growing season that update annually. The farm has a 36 foot-wide implement to apply N at a speed of 4.9 miles per hour in the field and a field efficiency of 75% allowing the farmer to work 16 acres per hour taking the farmer 94 h to complete post-planting N application on all 1500 acres. If the farmer works 15 h per day and works six days per week (e.g. does not have every day of the week available for fertilizer application during the specified period), given 92 average hours suitable over the specified application dates from June 13 to June 23, all 1500 acres will be completed by June 23 in 18 out of 35 years (51% of the time) that data are available for this location. Close inspection of Fig. 4 indicates that over 1500 acres could be completed by June 30 at least 95% of the time if another week is available (e.g., post-planting N can be applied through the V10 growth stage).

The economic analysis (Fig. 5) that integrates the completion percentile for the 1500 acre example indicates that the expected net benefit of a post-planting N application is $20,000. The table shows that an additional application expense of $23,000 was incurred. Because all input acres were completed, there was no yield loss due to unfertilized acres and there was a yield gain of 5 bu/ac, resulting in an economic benefit of $34,000. Our input in Fig. 1 also assumed that 15 lb N/ac were saved from a split N application, resulting in a nitrogen savings of $9000. The assumptions of benefits and penalties, as well as price, entered in Fig. 1 greatly impact the results of the economic analysis.

Continuing the example in Fig. 5, the average number of acres completed is only 1475, or just short of the user input value of 1500 acres. The average net benefit from fully fertilizing 1475 acres and leaving 25 acres without a second application is $15,000. The 25 acres not receiving the second N application had a yield loss of 44 bu/ac at a cost of $5000. The yield gain decreased from $34,000 to $33,000 because the yield benefit was not realized on all 1500 acres. The nitrogen saved value remained the same because all 1500 acres, even the 25 not fully fertilized, were credited with the 15 lb N/ac reduced N application rate.

The worst-case outcome over all of the 35 years of data available is that only 172 acres could be completed by June 23 resulting in a net loss of $253,000. The other end of the spectrum is the best case scenario, where in two years out of 35 the farmer could have completed over 2171 acres in the application window specified. The best case scenario indicates the cushion on the number of acres that could have received a second N application; the net benefit is the same as the Input Acres completed scenario because there are only 1500 actual acres to complete.

For this example, the costs and returns from splitting N application are equal (net benefit = $0) whenever 1401 of the 1500 acres of post-planting N are able to be applied, which happens 66% of the time for this location. Some locations have fewer years of data available to base these probabilities on.

4. Summary

The Split N tool developed by the Useful to Usable (U2U) project incorporates climate and USDA data with agronomic research to enable farmers to analyze the managerial and economic impact of an in-season N application. In-season N applications have the opportunity to benefit farmers and society, but they also increase the risk to farmers.

Favorable expected economic results of in-season N application are common but not guaranteed. The Split N tool moves traditional partial budget analysis of a management alternative from a deterministic result to probabilistic results. Careful analysis of the results allows for better crop management. For example, sensitivity analysis can be performed to examine different planting dates and estimated growth stages that allow for surface application. The agronomy literature is not settled on the yield benefits or reduction in annual N from in-season application so the user can modify that input and quickly observe the results for their farm. Extremely risk averse producers may feel comfortable experimenting with split N applications on the number of acres in the worst case scenario included in the output.

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